

# Quantum oscillations observed in graphene at microwave frequencies

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## Abstract

We have measured the microwave conductance of mechanically exfoliated graphene at frequencies up to 8.5 GHz. The conductance at 4.2 K exhibits quantum oscillations, and is independent of the frequency.

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The discovery [1] that graphene, a single atomic layer of carbon, can be produced by mechanical exfoliation of graphite has resulted in an explosion of research activity [2, 3]. Interest in graphene arises from its “Dirac” spectrum, which resembles that of relativistic particles [4, 5]. This spectrum gives rise to characteristic quantum oscillations in the magnetoresistance, and for sufficiently high magnetic fields and low disorder to the quantum Hall effect [1, 4, 5]. There is also great interest in graphene for potential applications, including microwave transistors, which were demonstrated [6, 7] to have cutoff frequencies up to 100 GHz. A recent study [8] of a graphene-loaded coplanar waveguide at room temperature and zero magnetic field showed that reasonable impedance matching to 50- $\Omega$  systems is possible.

In this paper we present a study of the microwave two-terminal conductance of mechanically exfoliated graphene. Our measurements are carried out on relatively low-mobility ( $\mu \sim 1000 \text{ cm}^2/\text{V}\cdot\text{s}$ ) samples at 4.2 K and in magnetic fields ( $B$ ) up to 8 T. Quantum oscillations of the conductance are observed up to our maximum measuring frequency ( $f$ ) of 8.5 GHz, both as a function of magnetic field and carrier density. To within the accuracy of our measurement, the conductance remains frequency independent from dc up to 8.5 GHz, consistent with  $2\pi f\tau \ll 1$ , where  $\tau$  is the transport relaxation time of the graphene ( $\sim 10$  fsec for our samples).

Fig. 1 shows a schematic of the measurement set-up. A graphene flake mechanically exfoliated from bulk Kish graphite is placed on top of a  $\text{SiO}_2/\text{Si}$  substrate, and a Ti:Au metal film is patterned as shown using electron-beam lithography. The graphene flake connects a driven center conductor and a grounded outer conductor. The Si substrate is mounted in a fixture which uses  $\sim 1$  cm long planar transmission lines between the substrate and coaxial connectors. The planar lines in the fixture are gold-wire bonded to the metal on the substrate. The connectors in the fixture attach to coaxial cables connected to a room-temperature network analyzer. The graphene conductance ( $G$ ) affects the microwave transmission coefficient, acting essentially as a load across a 50- $\Omega$  transmission line, so that larger  $G$  produces lower transmission. In contrast to most dc experiments [5, 9–12], the graphene in this set-up is connected at two terminals, so the measured conductance can include effects of contact resistances.

In order to minimize capacitive losses, we carefully chose the room-temperature resistivity of the Si substrate used as gate electrodes in this experiment to be 0.01 to 0.02  $\Omega\cdot\text{cm}$ . At the experimental temperature of 4.2 K, the conductivity of this substrate is sufficiently

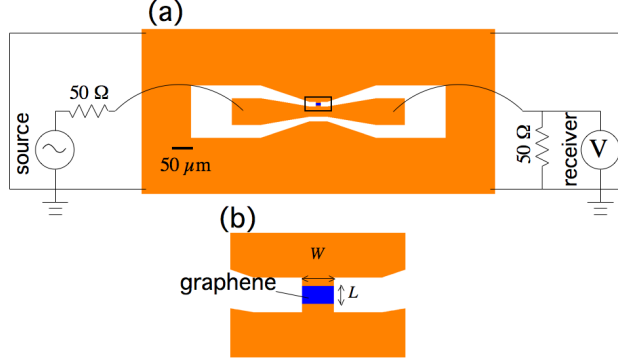


FIG. 1: (a) Schematic of the microwave circuit connected to the graphene device. Orange regions represent the metal film contact pattern deposited on  $\text{SiO}_2/\text{Si}$ . (b) Expanded view of the graphene flake and the nearby contact pattern connected to it (indicated with a rectangular box in 1a).

low that the current through the graphene sample dominates. We verify this condition by measuring a piece of the same  $\text{SiO}_2/\text{Si}$  wafer with the metal film pattern but without graphene. The substrate conductivity is still large enough to allow control of the graphene carrier density and sign by applying a backgate voltage ( $V_g$ ) between the graphene and the substrate.

We show results from two graphene flakes: sample 1, with length  $L \approx 2 \mu\text{m}$  and width  $W \approx 42 \mu\text{m}$ , and sample 2, with  $L \approx 1.6 \mu\text{m}$  and  $W \approx 15 \mu\text{m}$ . From the measured resistivity at large carrier density, we found dc electron and hole mobilities of  $0.5$  to  $1 \times 10^3 \text{ cm}^2/\text{V-s}$ , with the hole mobility higher than the electron mobility as has been observed elsewhere [13, 14]. The onset fields of the Shubnikov-de Haas oscillations result in an estimate of mobilities [15]  $\mu \sim 2.2$  to  $4 \times 10^3 \text{ cm}^2/\text{V-s}$ . The mobilities are rather low compared to those of typical mechanically exfoliated graphene samples [12, 16]. This low mobility might be due to contamination during the device fabrication process of the large electrodes for microwave contacts or to the relatively large sample sizes, which tend to have large inhomogeneity. The samples for which we show data have backgate voltages at the charge neutral point ( $V_{\text{CN}}$ ) within 5 V of zero.

Fig. 2a shows  $P$ , the microwave power transmitted through graphene sample 1, as a function of  $B$  at  $f = 8.5 \text{ GHz}$  with  $V_g = 80 \text{ V}$  so that the graphene electron density is  $\sim 5.4 \times 10^{12} \text{ cm}^{-2}$ . Quantum oscillations are evident for  $B$  above about 4 T. Local maxima in transmission correspond to local minima of conductance, and are taken as integer Landau

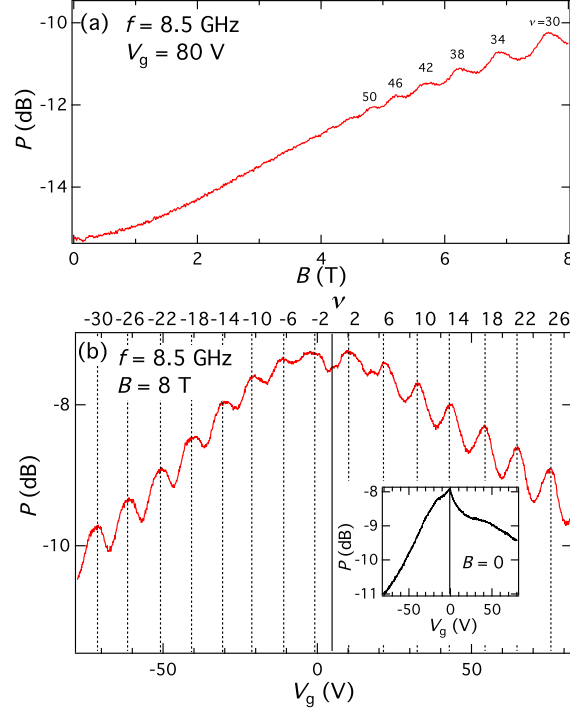


FIG. 2: (a) Log-scaled transmitted power ( $P$ ) as a function of the magnetic field ( $B$ ) at  $f = 8.5$  GHz and a backgate voltage ( $V_g$ ) of 80 V, from sample 1. (b)  $P$  vs  $V_g$  at  $f = 8.5$  GHz and  $B = 8$  T, from sample 1. Integer filling factors ( $\nu$ ) label dotted vertical lines at the local maxima. The inset shows  $P$  vs  $V_g$  at  $B = 0$  from sample 2.

fillings ( $\nu$ ) as considered in detail in Ref. 20. Fig. 2b shows  $P$  vs  $V_g$  in a magnetic field of 8 T. The quantum oscillations are clearly visible in this trace as well, and are superimposed on a broad peak around  $V_{CN}$ . At  $B = 0$ , the peak in  $P$  vs  $V_g$  around  $V_{CN}$  is present without the quantum oscillations, as shown in the inset.

For graphene admittance ( $Y$ ) sufficiently small in magnitude, the microwave attenuation of the fixture with graphene can be linearized as  $\log |s_{21}/s_{21}^0| = C_F(f)G$ , where  $s_{21}$  and  $s_{21}^0$  are transmission coefficient  $s$  parameters [17] between the fixture connectors with and without graphene.  $G = \text{Re}(Y)$ , and  $C_F(f)$  is a frequency-dependent constant associated with the fixture.  $C_F$  is obtained from room-temperature measurements of the fixture with standard resistors (carbon paint) painted onto the microwave pattern shown in Fig. 1 with an undoped substrate. Planar simulation software [18] was used to verify that there was no effect of the geometry of the standard resistor differing from that of the graphene flake. From

an analytical model of the fixture, which took into account the lengths within the fixture, the conductor losses, and the reactances of the bond wires [19], we find the linearized attenuation to hold to within about 5 % for  $G \leq 9$  mS for the case of  $Y$  having small argument. We verify that  $Y$  has small argument for our experimental conditions by looking at the phase shift of the microwave transmission as  $V_g$  is varied. At any frequency in the experiment this phase shift is within  $7^\circ$ , which is within experimental error of that expected for  $Y$  purely real. At fixed  $f$  we obtain  $\Delta G = G(V_g) - G(V_{CN}) = C_F^{-1} \log(P(V_g)/P(V_{CN}))$ .

Fig. 3 shows  $\Delta G$  vs  $V_g$  at various frequencies from dc to 8.5 GHz. The two-terminal dc conductance is measured between the contact center line and the ground plane with a lock-in technique. The  $B = 0$  data shown in the inset is obtained from sample 2, and the charge neutral point dc conductance is  $G(V_{CN}) = 1.6$  mS. The 8-T data in the figure is from sample 1, and has dc  $G(V_{CN}) = 0.6$  mS. Clear quantum oscillations are apparent, but possibly due to the low mobility of our samples,  $G$  does not appear to exhibit quantized values[20] as would be expected if the quantum Hall effect were developed.

For both data sets in Fig. 3,  $\Delta G$  vs  $V_g$  is clearly independent of  $f$  within experimental error. At  $B = 8$  T the maximum percent difference between microwave measured  $\Delta G(V_g)$  and the conventionally measured dc  $\Delta G(V_g)$  is about 20 % for  $V_g < 0$ , and 5 % for  $V_g > 0$ . For  $B = 0$ , the microwave  $\Delta G(V_g)$  is within about 15% of the dc  $\Delta G$  for both positive and negative  $V_g$ . Additional data for lower nonzero  $B$  likewise shows no  $f$  dependence of  $\Delta G$  to within our experimental accuracy. Though we measure  $\Delta G$  only, its frequency independence is a reliable indicator that the absolute conductance  $G$  must be frequency independent as well.

The  $f$ -independent behavior of graphene conductance is entirely consistent with the low- $f$  limit,  $2\pi f\tau \ll 1$ , where  $\tau$  is the transport relaxation time of the graphene carriers. This is reasonable in light of estimates of such time scales from theory[21] and from dc mobility[16] and magneto transport measurements[22]. All give transport and quantum scattering times for mechanically exfoliated graphene of order 10 fsec for  $n_c \sim 10^{12}$  cm $^{-2}$  and  $\mu \sim 1000$  cm $^2$ /V-s. Our microwave frequencies are also too small to resolve inter Landau level transitions[23–26] in the magnetic field. Our measuring temperature is much larger than  $hf/k_B$  (where  $h$  is the Planck’s constant and  $k_B$  is the Boltzmann constant), so that quantum critical effects [27] are also not expected to result in the measured  $f$  dependence [28].

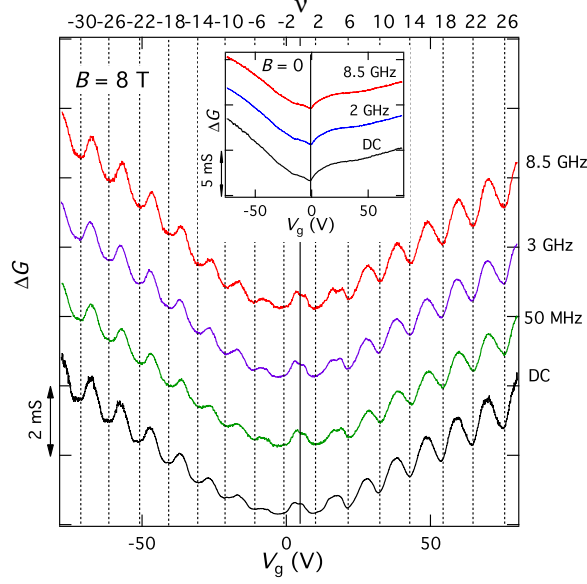


FIG. 3:  $\Delta G$ , the graphene conductance shift from its charge neutral point value, vs backgate voltage ( $V_g$ ) for sample 1 at  $B = 8$  T, at various frequencies ( $f$ ) from DC up to 8.5 GHz. Traces are offset for clarity. The charge neutral point voltage,  $V_{CN} = 4.7$  V, is indicated with a vertical solid line. The minima of the small quantum oscillations are indicated with vertical dashed lines with their corresponding  $\nu$  shown on the top axis. Inset:  $\Delta G$  vs  $V_g$  at  $B = 0$  as measured in sample 2.

In summary, we have measured the conductance of low mobility, mechanically-exfoliated graphene devices with contact patterns designed for microwave measurements on the  $\text{SiO}_2/\text{Si}$  chip, at frequencies up to 8.5 GHz and at a temperature of 4.2 K. The conductance, which at high  $B$  includes quantum oscillations vs magnetic field and backgate voltage, is  $f$  independent to within the accuracy of our measurements. We thus conclude that the graphene magnetotransport remains essentially in the dc limit up to at least 8.5 GHz.

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